Report 2177

SPECTRAL REFLECTANCE EVALUATION OF CAMOUFLAGE DETECTION PHOTOGRAPHY

May 1976

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U.S. ARMY MOBILITY EQUIPMENT
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For artificial camouflage materials to react the same as foliage toward camouflage detection photography, it is necessary for the colors to possess the same characteristic spectral curve as foliage. Camouflage detection photographic film capitalizes on the high infrared reflectance region and very low red region reflectance of deciduous foliage to create a high contrast between foliage and other materials. A specific combination of these high infrared

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and low red region reflectances excites the specific layers of the film to cause the artificial camouflage to react the same as foliage. The program establishes the allowable latitude in camouflage detection parameters, particularly red reflectance, infrared reflectance, infrared/red ratio, and the shape of the curve from the red to the infrared regions, plus optimum characteristics for matching various types of foliage.

PREFACE

The investigation was performed by Fred Lafferman under the supervision of Emil J. York, Chief, Laboratory 9000. Appreciation is expressed to Mr. Albert Perri, Countersurveillance Division, Laboratory 4000, for his assistance.

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SPECTRAL REFLECTANCE EVALUATION OF CAMOUFLAGE DETECTION PHOTOGRAPHY

I. INTRODUCTION

1. **Subject.** The object of this investigation was to conduct an analysis of pigment formulations for green camouflage colorants from the standpoint of color rendition on camouflage detection (CD) film as a function of spectral properties. The work establishes the allowable latitude in CD parameters, particularly red reflectance, infrared reflectance, infrared/red ratio, and the shape of the curve from the red to the infrared regions, plus optimum characteristics for matching various types of foliage.

2. **Background.** In the past, it never has been established what type of spectral curve was actually required to produce the type of visual color on CD film that actual foliage provides. Color and spectral reflectance requirements always have been written to include a maximum-minimum reflectance in the red and infrared region plus a minimum ratio between the two. For the camouflage nets, it has been the policy to require a minimum reflectance at 700 nanometers. Based upon the interpretations of CD photography, these values were established for each camouflage green color to assure optimized color responses for CD film. Several problem areas have arisen because of these requirements. In many instances, the requirements have caused CD photographs to produce colors that were too pure and too red. In addition, such requirements have caused the development and production of these paints and coatings to be extremely difficult. The use of extremely expensive organic pigments, costing approximately $20/lb., was required to meet the camouflage net requirements of spectral reflectance.

These requirements always have been based on theory that has originated back many years of visual and infrared photo interpretation of foliage. There existed no means of determining spectral reflectance without a field test. CD photographic film capitalizes on the high infrared-reflectance region and very low red-region reflectance of deciduous foliage to create high contrast between foliage and other materials. For artificial camouflage materials to react the same as foliage toward CD film, it is necessary for the colors to possess the same characteristic spectral curve as foliage. A specific combination of these infrared and low red-region reflectances excites the specific layers of the film to react the same as they would react to foliage. From the theories established, it has been determined that to avoid high color contrast between artificial camouflage and foliage where photographed with CD film, a maximum red-region reflectance must be established so that only the correct amount of the magenta layer will be exposed. Similarly, a minimum infrared reflectance has to be required so that the cyan layer will be fully exposed.

This work was performed to determine not only that which is described above but also a maximum-minimum range from 600 to 900 nanometers within which the curve must fall. There is no need to specify precise red and infrared reflectances for each individual camouflage green color. The red region is basically dependent upon the visual reflectance limits established for that specific color. Although CD photography is also dependent upon the green region of the spectrum (visual reflectance), the range of color space that is established for the camouflage colors is much narrower than that of foliage and, thus, does not significantly affect the actual visual color rendition on CD film. Therefore, the work described within this report will encompass only the spectral range of 600 to 900 nanometers.

II. INVESTIGATION

3. **Procedure.** Numerous coatings were formulated in the dark, light, olive, and forest green colors exhibiting varying degrees of spectral reflectance characteristics. These coatings were applied on various types of substrates, spectral reflectance curves were run by the Diano Hardy Spectrophotometer, and CD photographs were taken.

The visual and infrared spectral curves were obtained both from existing camouflage net samples and paints and from newly formulated coatings. This was performed to assure that there was an extremely wide range of spectral curve shapes and reflectances. It was essential to have curves that possessed a large range of both high and low red-region reflectances, slow and fast rises into the infrared, and high and low infrared reflectances. It was also essential to have various types of interactions between these characteristics. CD photos were taken on each one of the samples. These photographs were used for standardization of foliage color and for correlation of the samples to foliage both spectrally and visually.

III. DISCUSSION

4. **Color Difference of Samples and Foliage.** Approximately six types of foliage were used as standard for color reproduction on CD film. Since the actual visual color of these foliage samples appeared to be the same on CD film, it was felt that the best way to determine optimum spectral wavelength distribution was by visual color difference measurements. By this, maximum color differences could be established which would allow an exact determination of spectral curves to establish a maximum-minimum wavelength reflectance range. The initial work was coordinated with the Countersurveillance and Topographic Division, Laboratory 4000, U.S. Army Mobility Equipment Research and Development Command, which has written a computer program establishing visual color responses (trichromatic and chromaticity coordinates) of spectral curves toward CD photography. Spectral curves of all the samples being evaluated were subjected to this computer program. The printout gave trichromatic

coefficients for each sample plus the foliage samples for CD photography. These samples were then compared to the standard foliage samples by the National Bureau of Standards (NBS) color difference equations. Several problems immediately arose. It is a known fact that NBS color difference is not equatable throughout color space, especially in the red-blue regions which are the basis for CD photography. Another problem area was the correlation of color difference between a designated sample and the various foliage samples. The third significant problem was the degree of allowable color difference error.

5. **Color Rendition on Camouflage Detection Film.** The computer program, developed by the Countersurveillance and Topographic Division, is capable of predicting the color photographic response of a given spectral reflectance curve under a variety of conditions of environment, camera parameters, and development procedures and allows for variations of these factors in any combination of ways desired. With the program, one is able to predict the color photographic response of a given spectral reflectance curve. When the above factors are varied, the spectral reflectance of a proposed camouflage material can be determined as to whether it possesses a satisfactory photographic color match to a given background or set of backgrounds. The program can also determine the conditions under which a color match is not successful. Therefore, the computer program can pretest proposed spectral curves and evaluate the spectral limitation of pigment formulations.

6. **Color Difference by CIE 1976 L* A* B* Color Difference Space.** Because of the difficulties with the NBS color difference equation, it was determined that the International Commission on Illumination (CIE) 1976 (L*A*B*) color difference equation would be used because its formula is intended to yield perceptually uniform spacing of object colors. Although the use of L*A*B* color space solved the problem of uniform color space, there still existed nonuniformity between foliage samples. Although the visual interception of different foliages on CD film appeared the same, their trichromatic coefficients, based on the computer program, were significantly different. This caused color difference readings of each specific sample of the various foliages to vary considerably. Because of this, it was impossible to determine the exact degree of error that distinguished acceptable and nonacceptable spectral curves. This can be observed from Table 1. When the samples were calculated against different types of foliage, the errors changed considerably. Both NBS and L*A*B* errors are shown to emphasize the difference in errors between foliage samples.

Even if a correlation between foliage samples could be established, the degree of error desired could not. For example, depending upon the directional movement in color space, a 7.0 L*A*B* color difference error may or may not be within the tolerable limits of CD color rendition. A 7.0 error could produce an orange or gray visual color appearance if it moved in one direction from a foliage standard but would

Table 1. NBS Error Vs. L*A*B* Error

Sample	Y (%)	X	y	NBS Error 1	NBS Error 2	NBS Error 3	L*A*B* Error 1	L*A*B* Error 2	L*A*B* Error 3
Foliage 1	16.50	0.399	0.281						
Foliage 2	10.70	0.431	0.304						
Foliage 3	10.30	0.420	0.297						
Sample 1	13.20	0.384	0.278	6.176	14.162	11.449	3.772	10.906	8.851
Sample 2	11.30	0.409	0.283	2.842	6.146	3.798	1.651	6.146	5.159
Sample 3	13.10	0.372	0.253	9.570	17.755	15.002	10.835	18.475	16.444
Sample 4	17.30	0.368	0.259	13.191	21.630	19.008	12.962	20.137	18.558
Sample 5	11.30	0.452	0.320	13.972	5.633	5.500	13.549	6.066	8.838
Sample 6	14.50	0.437	0.300	11.546	6.288	8.208	10.481	8.497	9.956
Sample 7	15.00	0.453	0.305	16.555	8.833	12.459	14.525	10.752	13.371
Sample 8	16.50	0.416	0.287	8.532	9.447	9.190	9.915	12.292	12.500

remain within a satisfactory red-purple color range if it moved in another direction. If foliages possessed identical trichromatic coefficients, then a standard error could be established; but they don't. Therefore, a 7.0 L*A*B* error could be satisfactory with one type of foliage but poor with another. Because of the problems described in this and the previous paragraphs, it was determined that spectral curve evaluation could not be performed by color difference equations.

7. **Generation of Data.** Since the curves that were being evaluated basically do not take into account all types of interactions between various spectral regions, it was determined that such data (spectral curves) should be generated as would encompass the several types of variations in the red region, the rise into the infrared, and the infrared region. Five standard camouflage curves, which differ in all respects, were analyzed by computer. Since the computer program predicts trichromatic coefficients for CD photography, it was determined to take these five curves and to vary the red region, the start of the rise into the infrared, the end of the rise into the infrared, and the average infrared reflectance. All of these areas were varied plus and minus a specified percentage plus the relationships between the various regions. The trichromatic coefficients were then calculated for each curve generated. With the quantity of variations from the original five curves, it could be assured that all possible spectral curves from 600 to 900 nanometers would be evaluated.

8. **Establishment of a Three-Dimensional Plot.** As described previously, color difference equations will not produce direct relationships according to various types of foliage for visual color rendition on CD film; therefore, it was determined that an optimized, three-dimensional plot within color space is required to determine exact color comparisons to those produced by foliage. Dominant wavelength and excitation

purity, which are in direct relationship to Munsell's hue and chroma, along with visual reflectances and trichromatic coefficients were analyzed for each spectral curve that was being evaluated. By subjecting approximately 15 different types of foliage to the above evaluations, it was possible to determine the following criteria necessary for artificial camouflage to possess if it is to approximate the same color reproduction on CD film as does foliage: (1) exact trichromatic values and color-space range, (2) wavelength definition and visual color appearance, (3) visual reflectance range, and (4) purity of color. Since it is most desirable to possess color standards, the above criteria were transformed to Munsell notations, and a plot in color space for Munsell color was established. This plot can be seen in Figure 1. Since Munsell charts are separated according to value or visual reflectance, it was necessary to draw two connecting plots. These plots, which represent the basic color of foliage on CD film, encompass the hue range of 6RP to 1.25R and the chroma range of 7 to 12. A value range of 3.70 to 4.75, 10.13 to 17.60 percent reflectance, respectively, was determined based upon the previously mentioned dominant wavelength study. The red plot encompasses the value range of 3.70 to 4.00, and the blue plot encompasses 4.01 to 4.75. The intersection of the two plots is the common area for the entire value range. This Munsell plot within trichromatic color space will determine whether a corresponding spectral curve, after being subjected to the previously described computer program, will possess optimum color rendition on CD photography. A spectral curve with a specific value must fall within the correct Munsell plot for the value on the common area for it to be acceptable.

9. **Establishing the Optimum Spectral Curve Range.** From the above plot, it was then possible to determine an optimum spectral curve range that would produce optimum color rendition on CD photography. The chromaticity and trichromatic coefficients were generated by the computer program for over 200 spectral curves. These curves encompass those coatings and paint samples first described within this report plus those curves which were generated by the study of varying the spectral responses from 600 to 900 nanometers. This data was plotted within Figure 1, and an initial spectral range was developed. To assure that this minimum-maximum spectral range was correct, further theoretical curves were generated that varied selected areas of this spectral curve plot. When subjected to the computer program, any curve that possessed a value larger than 4.75 or a visual reflectance larger than 17.60 percent was determined to be outside of the limits. Those that did not fall within the correct Munsell plot for value were also determined a failure. Figure 2 represents the final plot of the limits of a usable curve. Table 2 lists the wavelengths with their corresponding minimum-maximum reflectances. The blank spaces from 600 to 660 nanometers indicate that there is no minimum reflectance for this range, and those from 780 to 900 nanometers indicate that there is no maximum. For curves that possess a red region greater than or equal to 9.0 percent, the allowable rise into the infrared is earlier than for those curves with a red region lower than 9.0 percent. The area between 660 and 680 nanometers which is bordered by the red and blue lines is only for those curves having higher than 9.0 percent red region. All other curves must fall on the inside of the blue line.

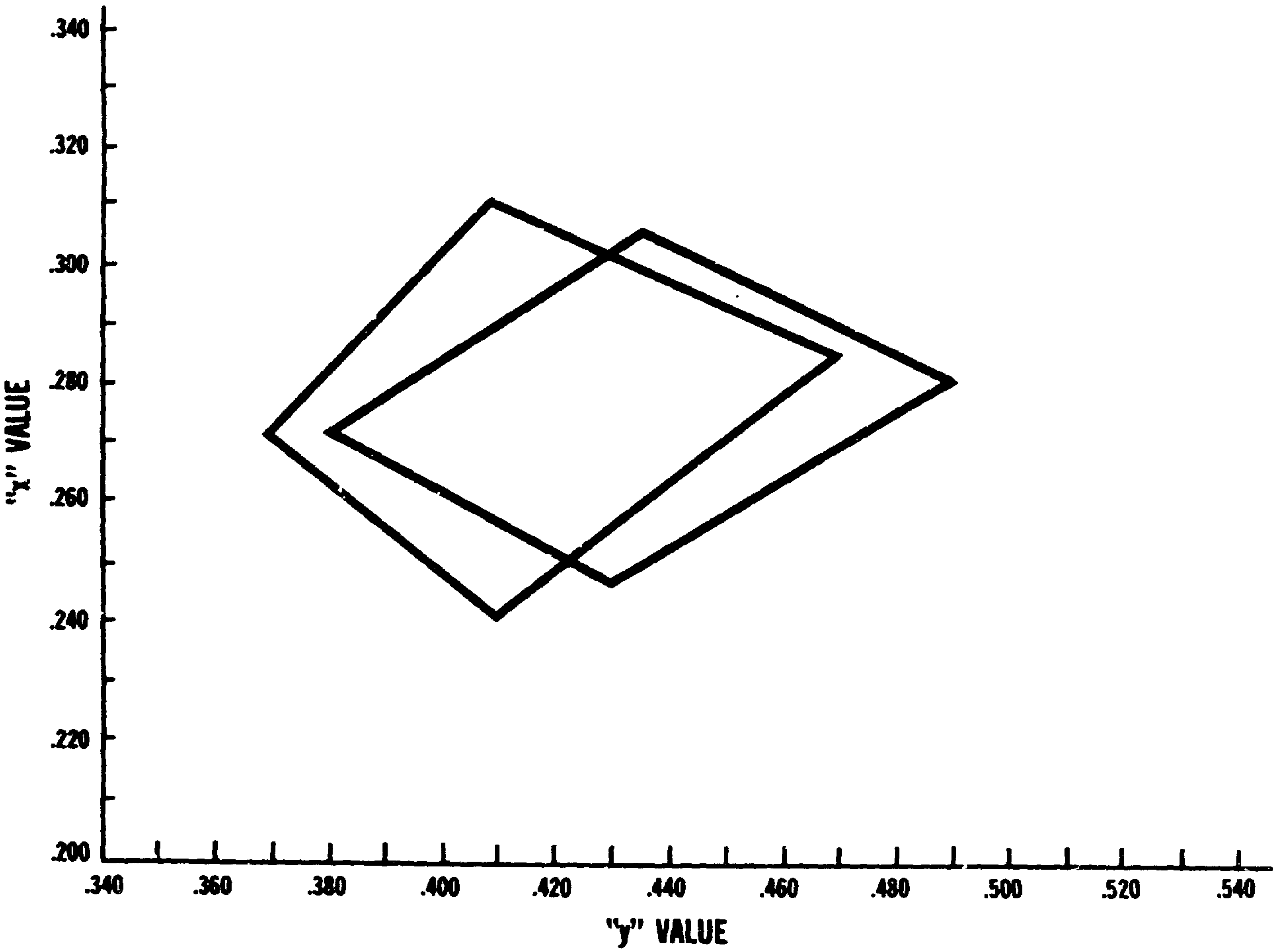

Figure 1. Munsell plots.

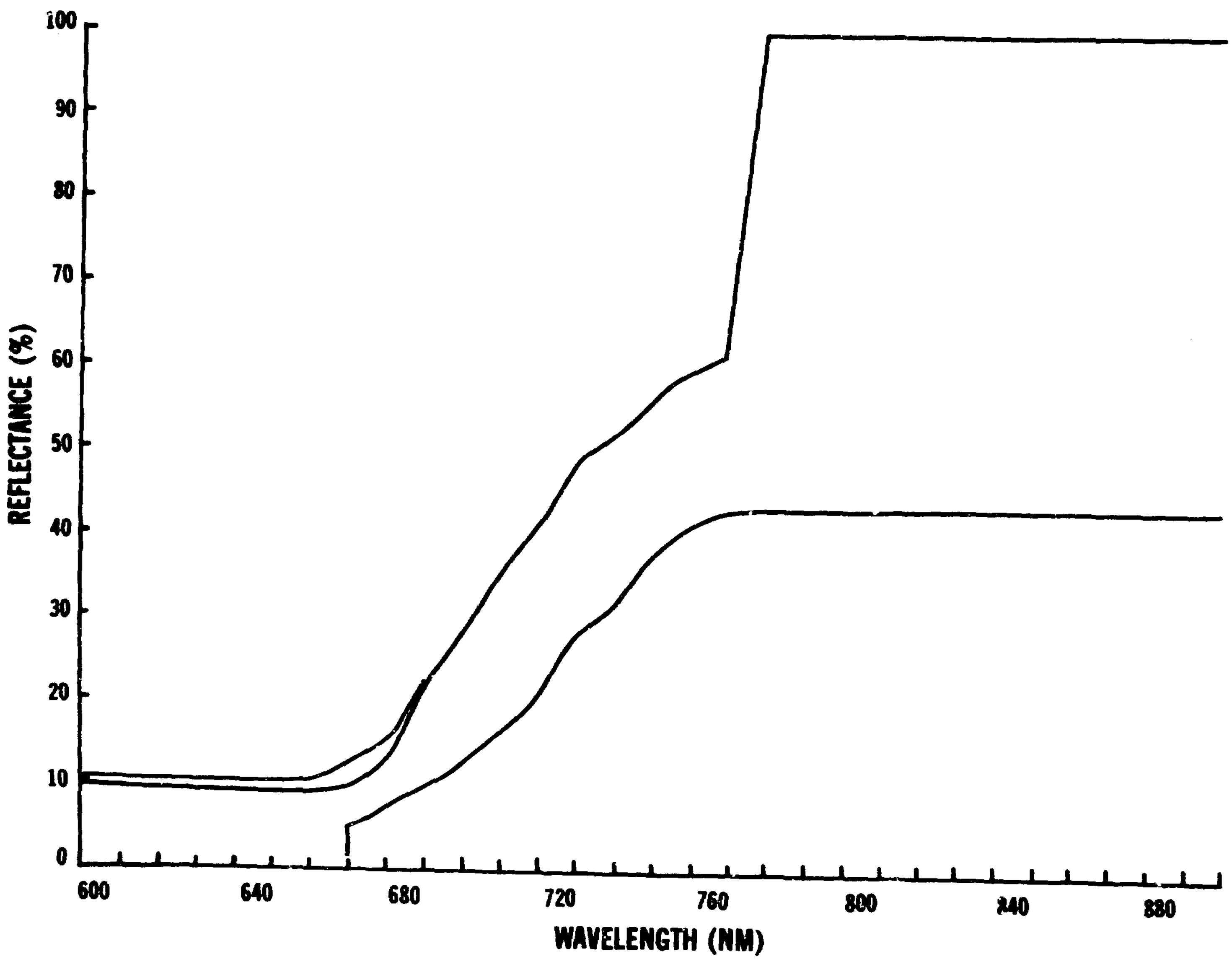

Figure 2. Minimum-maximum spectral reflectance limits.

Table 2. Minimum-Maximum Wavelength Definition

Wavelength	Maximum (%)	Minimum (%)	Wavelength	Maximum (%)	Minimum (%)
600	10.2	–	760	59.5	40.0
610	9.8	–	770	61.5	42.0
620	9.8	–	780	–	42.0
630	9.8	–	790	–	42.0
640	9.5	–	800	–	42.0
650	9.5	–	810	–	42.0
660*	9.5	–	820	–	42.0
670*	10.0	4.0	830	–	42.0
680*	13.0	5.8	840	–	42.0
690	21.5	8.5	850	–	42.0
700	28.0	11.0	860	–	42.0
710	35.8	15.0	870	–	42.0
720	41.0	19.0	880	–	42.0
730	48.5	27.0	890	–	42.0
740	51.8	30.0	900	–	42.0
750	56.0	36.3			

* NOTE: For spectral reflectance curves that possess a red-region reflectance $\geq$ 9.0 percent, the maximum allowable reflectances for these three wavelengths are as follows:

Wavelength	Maximum (%)	Minimum (%)
660	9.8	–
670	12.0	4.0
680	14.0	5.8

IV. RESULTS

10. Test Results. Figures 3 through 7 are illustrations of various curve shapes and reflectances from 600 to 900 nanometers. Figure 3 shows basically two identical curves except that the red one is within limits of CD response, while the blue one is not. What characterizes one from another is that the red region for the blue curve is too high compared to the master plot. This can be verified either by Figure 2, which has the blue curve outside of the limits, or by Figure 1, which has its trichromatics based upon the computer program plot outside of the limits. Table 3 represents the trichromatic coefficient based on CD film for the curves in Figures 3 through 7. Although the trichromatic values of x = 0.418 and y = 0.287 fall within the correct

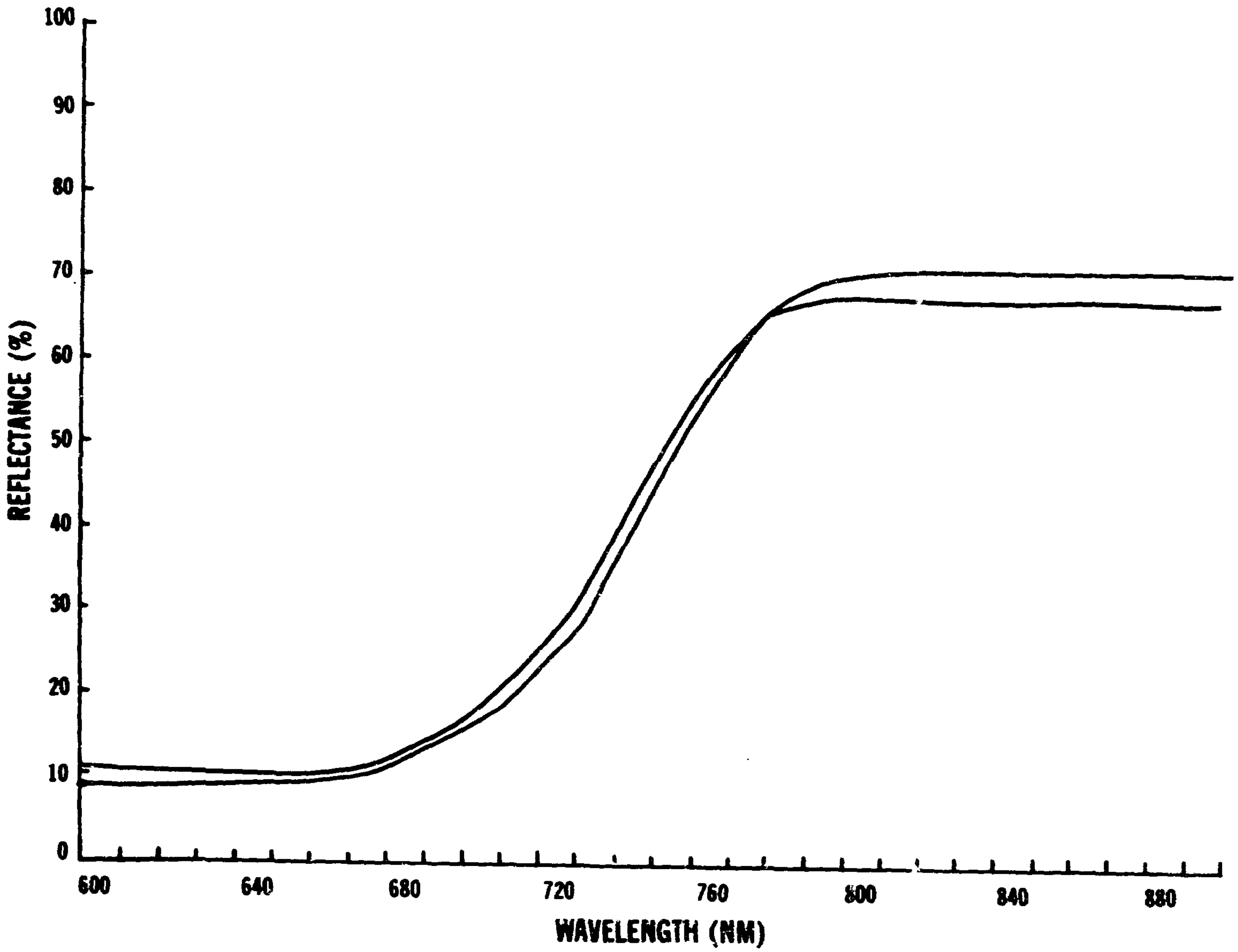

Figure 3. Curves 3 red and 3 blue.

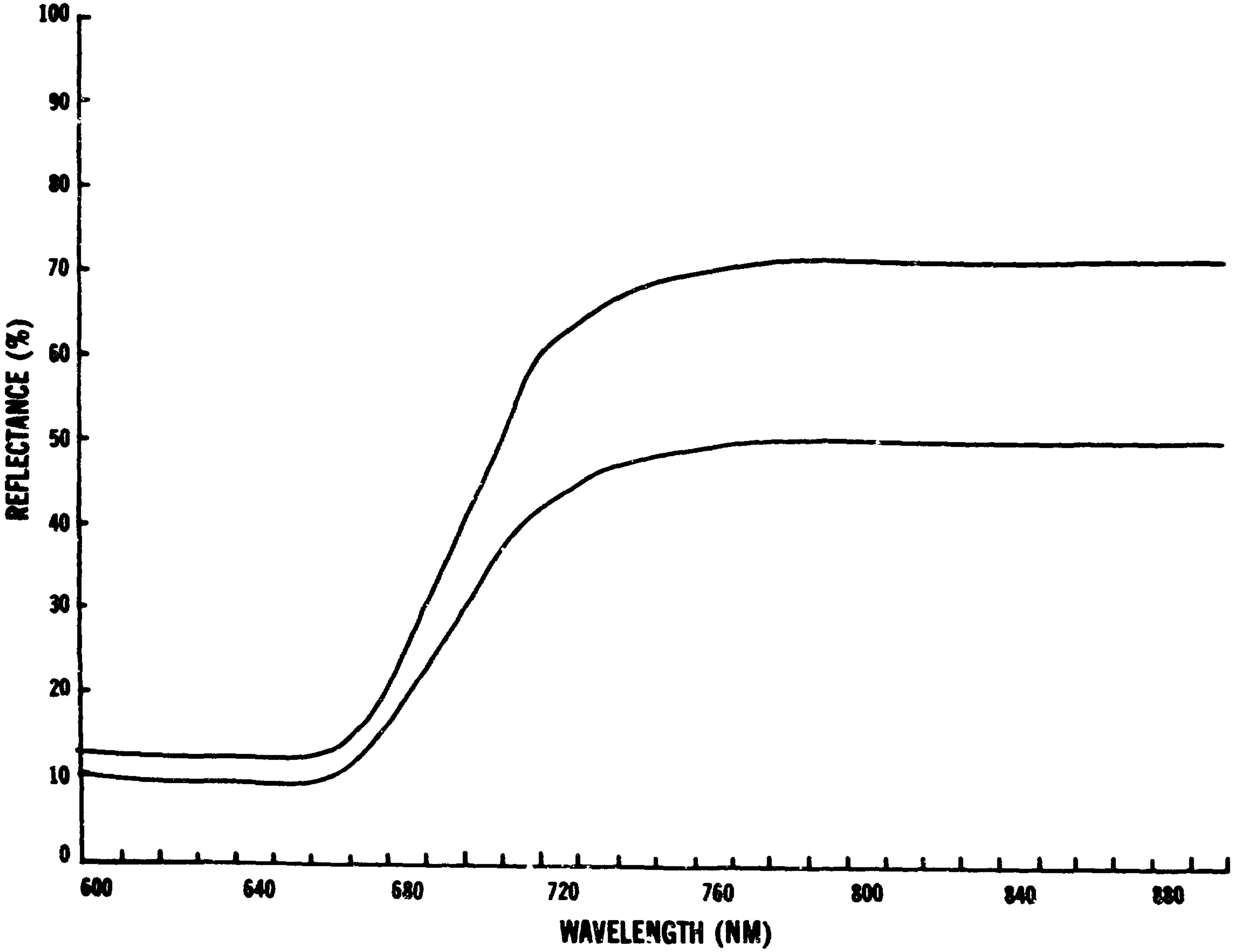

Figure 4. Curves 4 red and 4 blue.

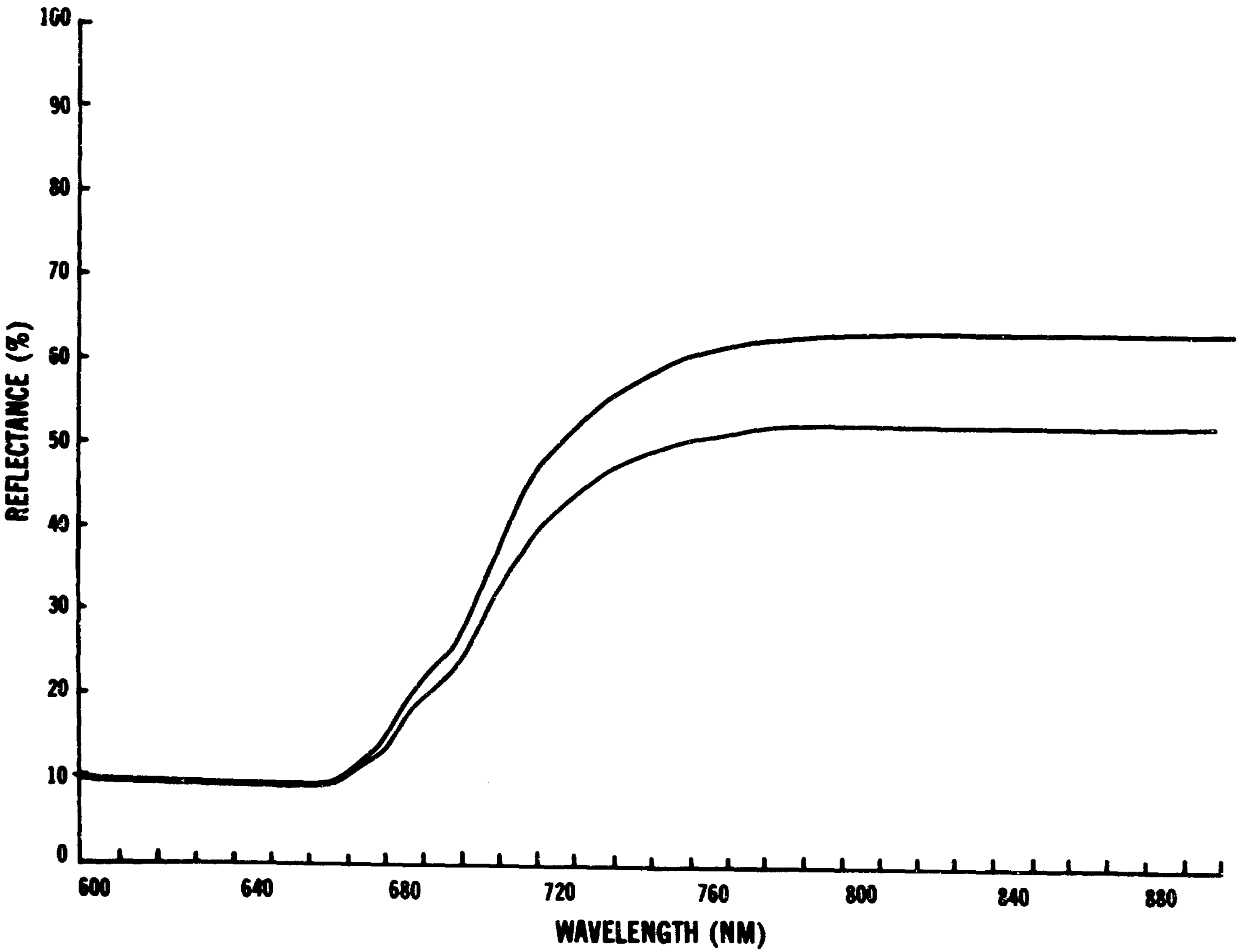

Figure 5. Curves 5 red and 5 blue.

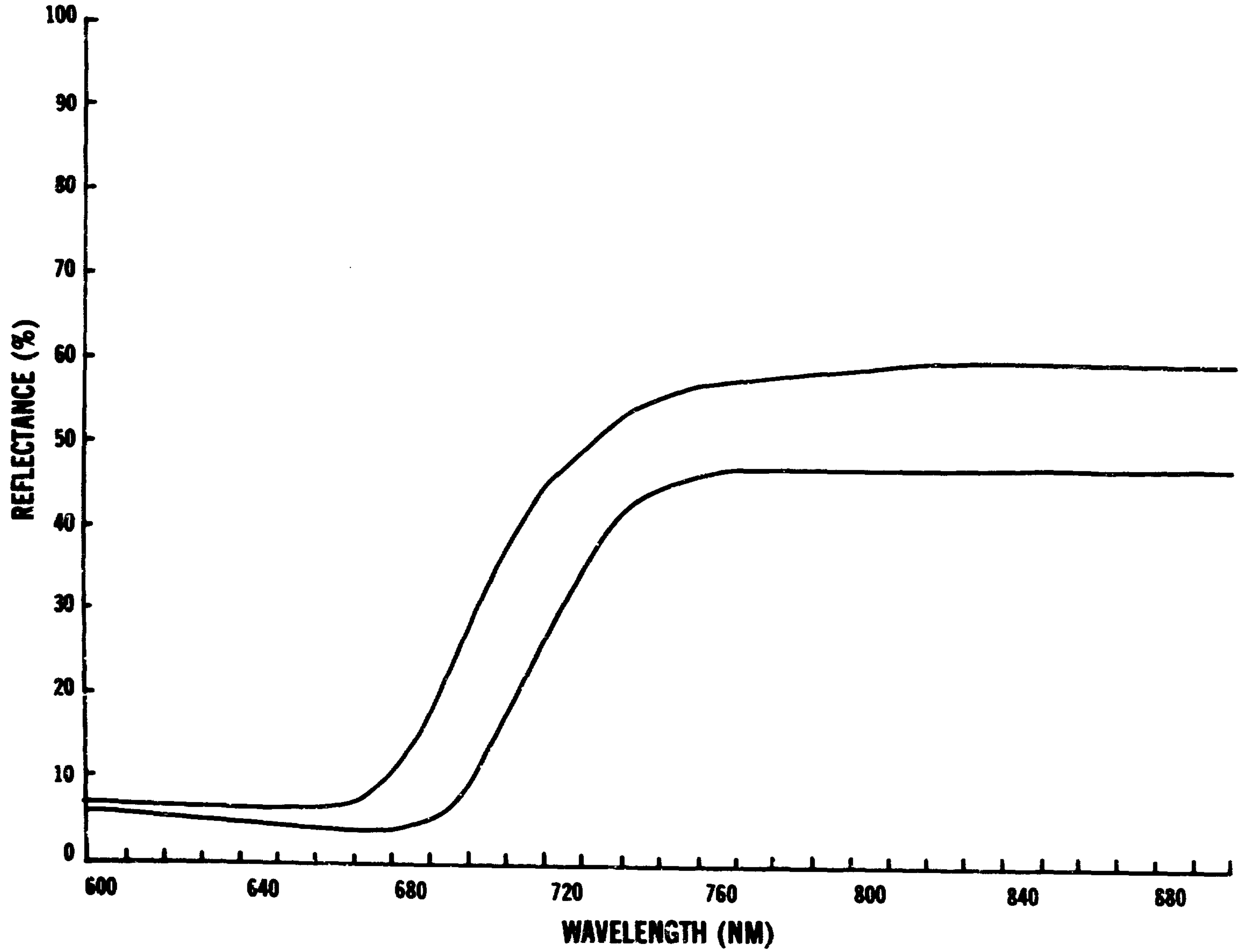

Figure 6. Curves 6 red and 6 blue.

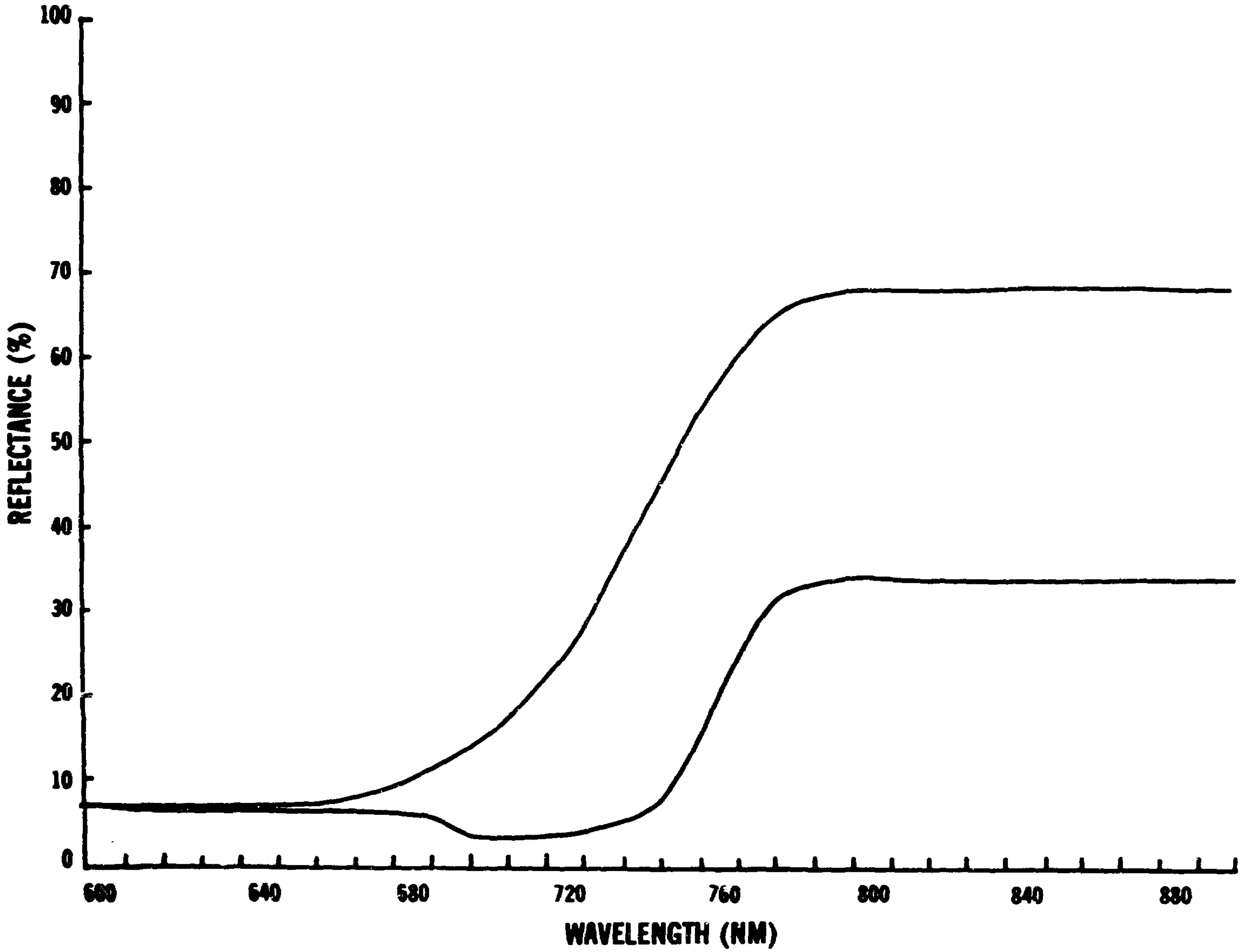

Figure 7. Curves 7 red and 7 blue.

plot, the visual reflectance Y is 18.20, which is higher than the maximum allowable. The visual reflectance on the red curve is 17.00 percent. This was verified by CD photos which showed the blue curve to be faded and washed out. Figure 4 shows a blue curve outside of the limits of Figure 2 because its extremely quick rise produces a visual reflectance of 22.99 percent, which is greater than the maximum allowable of 17.90 percent. The red curve is within the limits as indicated by Figure 2 and results in Table 3 corresponding to the plots in Figure 1. In Figure 5, two curves with the same red region are shown, but the blue curve rises faster into the infrared region. They both fall within the same Munsell plot, but the value of the blue curve is too high. Again, this was due to the early rise. In Figure 6, the red curve's slope is too steep based upon where it starts to rise. In this case, both curves are within the value range, but the red curve's trichromatic coefficients of x = 0.498 and y = 0.320 plot to the red side of the ellipse. The red curve happens to represent an old, dark-green camouflage net sample which originally was thought to be satisfactory until this study was performed. Since the slope was too fast and steep, the sample appears too red on CD film. Figure 7 shows a red curve that produces a pure red color on CD film because of the early rise and a blue curve that is much too blue on CD film because of its extremely slow rise. Again, these results can be confirmed by plotting the trichromatic coefficients and visual reflectances from Table 3 onto the Munsell plots. All of the experimental work has been confirmed by three methods: (1) Figure 1, Munsell plots, (2) Figure 2, curve plot, and (3) actual CD photographs.

Table 3. Chromaticity and Trichromatic Coefficients of Spectral Reflectance Curves from the CD Film

Spectral Curve	X	Y	Z	x	y
3 Red	25.18	17.00	16.65	0.428	0.289
3 Blue	26.51	18.20	18.71	0.418	0.287
4 Red	24.12	16.60	17.20	0.416	0.287
4 Blue	32.30	22.99	23.30	0.414	0.287
5 Red	24.48	16.70	18.68	0.409	0.279
5 Blue	26.91	18.00	17.53	0.431	0.288
6 Red	23.51	15.50	11.98	0.461	0.304
6 Blue	16.16	11.20	12.93	0.401	0.278
7 Red	22.28	15.00	11.90	0.453	0.305
7 Blue	6.92	6.00	8.06	0.330	0.286

11. **Red-Infrared Ratio.** This newly developed curve plot now indicates that spectral curves that were believed to be ideal for CD photographs, as were those in the early camouflage screen and paint systems, were actually producing poor photo comparisons with foliage. It is not necessary now to specify particular red- and infrared-region reflectances or a minimum reflectance at 700 nanometers as our recent camouflage specifications did. However, a curve cannot be produced that will exhibit the maximum red-region reflectance and be expected to possess camouflage properties. Although the curve may fall within the minimum-maximum limits, from 600 to 900 nanometers, it still may possess poor camouflage characteristics. As in the previous camouflage specifications, there still must remain a relationship between the integrated averages of the infrared and red regions. Based upon the spectral study, a minimum of 5.20 average of red to infrared reflectance must be maintained.

V. CONCLUSIONS

12. **Conclusions.** Based upon the previous theories of camouflage, many of the spectral reflectance curves that met these requirements now have been determined, based upon present theory, to actually be too red and bright on film. Many of these curves fell outside of this newly developed spectral curve plot. There is now no need to specify precise minimum-maximum reflectances for the red region, the infrared region, and the reflectance at 700 nanometers. From this study, it is now possible to determine the following criteria necessary for artificial camouflage to possess if it is to approximate the same color reproduction on CD photography as does foliage: (1) exact trichromatic coefficient and color-space range, (2) wavelength definition and visual color appearance, (3) visual reflectance range, and (4) purity of color. Acceptable color of CD film based upon these criteria produces a Munsell plot which encompasses the hue range of 6RP to 1.25R, a chroma range of 7 to 12, and a value range of 3.70 to 4.75. Figure 2 shows the final plot within which a curve has to remain in order to possess the correct Munsell color as described above. A minimum red-infrared reflectance ratio of 5.20 must be maintained.

One other requirement must be maintained if these results are to be valid: The coating surface must be completely matt because if it is not the specular reflectance (glass) will cause the color representation on CD film to completely fade and wash out.

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